

## INDUCTION HEATING

The present invention relates to induction melting. In particular, but not exclusively, the present invention relates to a method and apparatus for melting a target material such as glass in a melting vessel using two or more induction heating coils. The mutual induction of current in a non-energised heating coil adjacent to an energised heating coil is prevented so that the temperature in regions within the melting vessel can be carefully controlled.

There are many techniques which are known for melting materials and particularly for melting glass like materials. One of these techniques is induction heating in which electrical current is induced to flow in a current conducting melting vessel. These induced currents dissipate energy due to the Joule effect and this heating effect can be used to supply heat to material located within the melting vessel. If enough heat is supplied the material within the melting vessel melts.

A number of uses for such induction heating processes are known. One particular use is in the nuclear industry in which vitrification has long provided a safe long-term conditioning technology for radioactive waste material. In such a situation waste material which may be of low, medium or high-level radioactive waste is mixed together with a glass forming material such as glass frit in the melting vessel. The encapsulation of radioactive waste material within a glassy matrix is chosen because it is a mineral capable of including in its disordered structure many of the elements found in fission-product solutions

and other waste material. Once the waste material and glass forming material have melted and been mixed together they may be poured from the melting vessel into a storage canister. The storage canister can be used to  
5 define the final solid shape of the glass mixture once it solidifies and can also aid in a subsequent glass conveying process.

An example of this vitrification process is the  
10 continuous two-step vitrification process as exemplified by the Marcoule Vitrification Unit (AVM). In this vitrification process two steps are carried out. The first is evaporation-calcination of fission-product solutions. The second step is the vitrification of the  
15 resulting calcine. The initial evaporation-calcination step may be carried out with a rotating tube heated to a predetermined temperature. The elements from the input waste material in nitrate or oxide form flow into a second stage induction-heated metal pot. Glass frit or  
20 another glass former is added (for example borosilicate glass consisting mainly of  $\text{SiO}_2$  (silica),  $\text{B}_2\text{O}_3$  (boric anhydride),  $\text{Al}_2\text{O}_3$  (alumina) and  $\text{Na}_2\text{O}$  (sodium oxide) may be used. It is known that fission-product waste material may be incorporated to this glass forming material in  
25 quantities ranging from around 10 to 20%. In known vitrification facilities the metal pot is heated to between  $1000^\circ\text{C}$  and  $1200^\circ\text{C}$  using a 200 kW power generator operating at a frequency of 4kHz. As noted above the glass inside the metal pot is melted by thermal  
30 conduction upon contact with the metal wall.

However there are a number of problems which are known with such induction heating systems. One problem is that the induction heating coils which are used to heat the

melting vessel are run from high frequency generators which are becoming obsolete. This makes the replacement and/or servicing costs high.

- 5 Another problem is that arcing between contactors used to supply power to the heating coils has been observed. The arcing causes failure of the contactors which must be replaced. This is expensive and time consuming.
- 10 A further problem is that operating the induction heating elements at a high frequency of around 4 kHz limits control of the temperatures attained in various regions within the melting vessel. This is because penetration depth of a high frequency electromagnetic field limits
- 15 the depth to which eddy currents are induced and hence limits both the amount of heat generated within the vessel wall and inherently the thickness of vessel that can be used efficiently which in turn limits the life of the vessel due to thermal stresses.

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It is an aim of embodiments of the present invention to at least partly mitigate the above-mentioned problems.

- According to a first aspect of the present invention
- 25 there is provided a method for melting glass comprising the steps of:

providing a current conducting melting vessel within which glass can be melted;

- providing at least two induction heating coils at
- 30 selected locations proximate to said melting vessel; and

selectively supplying power to said coils to thereby selectively energise said coils; whereby

the mutual induction of current in a non-energised heating coil adjacent to an energised heating coil is

prevented via a switching element in power supply circuitry associated with said non-energised coil.

According to a second aspect of the present invention  
5 there is provided an apparatus for melting glass is induction melting comprising:

a current conducting melting vessel;

at least two induction heating coils provided at selected locations proximate to said melting vessel;

10 a plurality of power supply circuits each being associated with a respective one of said heating coils and being arranged for selectively supplying power to a respective coil to thereby energise that respective coil; wherein

15 each power supply circuit includes a switching element for preventing the mutual induction of current in a non-energised heating coil when an adjacent heating coil is energised.

20 According to a third aspect of the present invention there is provided a method for reprocessing waste material comprising the steps of:

locating said waste material together with glass forming material in a current conducting melting vessel;

25 applying power to at least one of a plurality of induction heating coils located proximate to said vessel to thereby heat said glass forming material; and

subsequently pouring a molten mixture of glass and waste material from said vessel into a storage container;

30 wherein

during said power applying step, at least one of said heating coils is energised and mutual induction of current in a non-energised heating coil adjacent said energised coil is prevented via a switching element in

power supply circuitry associated with said non-energised coil.

According to a fourth aspect of the present invention  
5 there is provided a method for melting a target material comprising the steps of:

providing a current conducting melting vessel within which said target material can be melted;

providing at least two induction heating coils at  
10 selected locations proximate to said melting vessel; and selectively supplying power to said coils to thereby selectively energise said coils; whereby

the mutual induction of current in a non-energised heating coil adjacent to an energised heating coil is  
15 prevented via a switching element in power supply circuitry associated with said non-energised coil.

Embodiments of the present invention provide a method and apparatus for melting a glass and waste material mixture  
20 using two or more induction heating coils. When only one of the induction heating coils is energised the mutual induction of current in an adjacent non-energised coil is prevented. Alternatively when adjacent coils are energised together power delivered to regions within the  
25 melting vessel associated with each of those coils is balanced. As a result embodiments of the present invention provide an induction melting process which can provide a much tighter temperature control by way of minimising the temperature differential attained through-  
30 out the vessel and contents, and prolonging vessel life where thicker walled vessels are implemented.

Embodiments of the present invention can operate at low frequency, for example 50 Hz. The lower frequency

electromagnetic field has deeper penetration and so can be used with a thicker walled vessel retaining its heat efficiency and thus providing extended vessel life.

5 Embodiments of the present invention will now be described hereinbelow, by way of example only, with reference to the accompanying drawings in which:

Figure 1 illustrates a vitrification process;

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Figure 2 illustrates an induction melting vessel; and

Figure 3 illustrates power supply circuitry for supplying power to an induction heating coil.

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In the drawings like reference numerals refer to like parts.

In accordance with an embodiment of the present invention  
20 figure 1 illustrates a continuous two-step vitrification process which uses in one of the steps an induction furnace to melt a mixture of glass and waste material. It will be understood that embodiments of the present invention may be used in this procedure however the  
25 invention is not limited to use in such an environment but rather is broadly applicable to induction melting in general.

In the vitrification process illustrated in figure 1  
30 waste material in a solution form which may for example be a fission-product from the nuclear industry is introduced into an inlet 11. This solution falls into a rotating kiln 12 which is effectively a rotating tube heated by a resistance furnace 13. The furnace produces

a first evaporation-calcination step and the solid calcine, which includes elements from the waste solution input at inlet 11 in nitrate or oxide form, falls through chamber 14 into the induction heating vessel 15. A glass former such as glass frit is added to the solid waste material entering the induction furnace through inlet 16. When melted this glass former provides containment glass within the matrix of which the elements of the waste material will be locked. A borosilicate glass is one particularly advantageous glass former. The metal pot 15 may be heated to temperatures between 1000°C and 1200°C using a induction heating method in which coils 17 may be selectively energised. When energised the coils act as a primary in a transformer element with the secondary element of the transformer being formed by the metal body of the melting vessel 15. As a result of the application of power to the coils an electrical current is induced in the body of the melting vessel. These induced currents cause a heating effect in the melting vessel and this heating effect is conducted to the contents of the melting vessel causing the glass and waste material to mix and melt. At an appropriate moment when a predetermined quantity of melted mixture is located in the melting vessel a tap 19 or other discharge means for opening an outlet 20 is opened to discharge molten material into a canister 21. The canister 21 is used to determine the final shape of the solid glass block which forms as the molten mixture solidifies. The canister may also include handles 22 or other means which aids the subsequent movement of the canister.

Figure 2 illustrates an induction furnace in more detail. The induction furnace 10 includes an electrical current conducting melting vessel 15 which may for example be

manufactured from a metal nickel-based alloy. The melting vessel has an inlet 23 formed by a neck region 24 of the melting vessel body 15. Waste material and glass forming material are input at the inlet 23. The melting vessel has a least one outlet 20 from which a mixture of the molten glass and waste material may be poured into a canister located below the melting vessel. A further aperture 25 may also be provided which can be used to drain the melting vessel during a refitment procedure. Both of the apertures 20 and 25 are formed by respective neck regions 26, 27 formed from the body region of the melting vessel. Each of the apertures 23, 20, 25 are associated with a respective induction melting heating coil 28, 29 and 30 respectively. By selectively energising these coils glass blockages forming seals on the apertures may be melted. In this way the apertures are opened as though a tap has been turned. It will be understood that embodiments of the present invention are not restricted to a mixing vessel having this particular shape and/or number of inlets and/or outlets. Likewise it will be understood that other forms of tap mechanism may be provided without the use of the induction heating coils 28, 29 and 30. It will likewise be understood that each of the tap coils requires a respective power supply circuit for selectively energising the coil when the seal on that respective aperture needs to be removed.

Four heating coils 31 to 34 form the coils 17 shown in figure 1 and are located proximate to the melting vessel. It will be understood that embodiments of the present invention are not limited to use of four coils. The coils are located close enough to the metal melting vessel so that when energised a current is induced in the melting vessel in a region associated with the respective



energised coils. As a result of the induced current flowing in the metal container the metal container itself heats up. This heat is transferred into the contents of the mixing vessel 15 and will after a predetermined amount of time act to melt the glass frit input at inlet 23. As the glass melts the atoms and molecules of the waste material become located in the glassy matrix. In this way because of its amorphous structure the glass accommodates the wide variety of elements found in spent fuel. The fission-product parts form bonds within the main components of the glassy vitreous matrix and these bonds act to lock the waste material within the glassy matrix.

Each of the heating coils 31 to 34 may be turned on and off by respective power supply circuitry so that one, two, three or four heating coils may be energised at any one time and in any combination. As a result of this fact the temperature gradients and temperature profiles of zones (or regions) within the melting vessel may be selectively controlled. It will be understood that more or less than four heating coils may be provided so as to provide control of the temperature in any area of the melting vessel.

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Figure 3 illustrates power control circuitry 40 which can be used to supply power to one of the induction heating coils. Each coil is provided with its own separate supply. When power is supplied to the coil the coil is energised and will then act as a primary coil of a transformer element. A region of the current conducting melting vessel 15 close to the coil will act as a secondary in which a current is induced to flow. By turning the supply of power to a coil on and off the

current induced in the melting vessel can be controlled and the associated heating effect thus also controlled. Coils adjacent to an energised coil may also be supplied with power to thereby energise the coils or may be non-  
5 energised. By selecting when coils are or are not energised by controlling the supply of power in the power supply circuit 40 associated with each separate coil the heating effect within the melting vessel can be controlled.

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In figure 3 the power supply circuitry is provided with a three phase 50 Hertz AC power supply 41. It will be understood that any other low frequency supply could be used. Around 50 Hz is particularly convenient because it  
15 represents a mains power supply in the UK. Two phases such as the supplies nominated as red and yellow are input into a circuit breaker 43 to provide protection to the circuitry during power surges/faults. In this way the phase selection is obtained by hard wiring the  
20 required phases at the outgoing side of the MCCB (circuit breaker) (43). Elements (42) are flexible couplings between the MCCB and the bus-bars from where the power is derived. These are not necessarily required. Fuses 44 and 45 are also provided to supply power to the circuitry  
25 via a step down transformer not shown for clarity.

A transducer 46 monitors incoming voltage characteristics and may be used to provide details of these indicating a supply voltage to a user. A supply power transducer 47  
30 receives as an input a current induced in a current transformer element 48 which monitors current in the red leg of the supply line. In this way the supply power may be identified across monitoring points 49 and 50. The current may be checked via monitoring points 51 and 52

and the voltage via monitoring points 53 and 54. Two safety contactors 55 and 56 each in a respective leg of the supply operate to break a circuit if an interlock occurs. An interlock is an external plant condition, or  
5 a safety trip, providing a means of shutting down vessel heating if required.

A tapped transformer element 57 acts as a coarse power level set to determine a range of power which may be  
10 supplied to the heating coil associated with the particular power supply circuitry. Four contactors are illustrated providing four possible settings for the power. It will be understood that embodiments of the present invention are not limited to the use of four  
15 settings.

A metal varistor 58 is connected in parallel across a supply node 59 in supply leg 60 and a return node 61 in return leg 62 for transient suppression to reduce  
20 transient spikes. An output voltage transducer 63 is connected to a node 64 in the supply leg 60 and a node 65 in the return leg 62 for monitoring the output voltage supplied to the inductor coil, via monitoring points (70) and (71).

25 Total current transducer element 66 has an associated inductive element 67 in the supply leg 60. The current induced in the inductive element 67 by the current flowing through the heating coil in the supply leg will  
30 give an indication of the total current which may be monitored at monitoring points 68 and 69.

A capacitor current transducer 72 and associated inductive element 73 provide an indication of the current

flowing through a capacitor bank 74 during a precharging and/or coil power supply operation as described hereinbelow. This current may be monitored across monitoring points 75 and 76. A further transducer 77 and  
5 associated inductive element 78 provide an indication of the current flowing through the return leg 62 of the supply circuitry 40. Monitoring points 79 and 80 are provided to supply this indication to a user monitoring the operation of the power supply circuitry. It will be  
10 understood that the monitoring can be an automatic process.

A first switching element 81 consists of a thyristor 83. The thyristor 83 acts as switch so that a current  
15 mutually induced within a non-energised heating coil by the effects of an adjacent energised heating coil are prevented.

Serially connected resistors and capacitors are connected  
20 in parallel and then the whole connected in parallel across the input and output of the thyristor 83 to act as a snubber so as to provide suppression of the load to reduce transient spikes.

25 A second switching element 84 formed by oppositely orientated thyristors 85 and 86 are connected in the supply leg 60 of the power supply. A snubber circuit formed by a serially connected capacitor and resistor connected in parallel with another serially connected  
30 capacitor and resistor are connected across the inputs and outputs of the two thyristors 85 and 86 in the second switching element 84. This is also to provide a snubber circuit to reduce transient spikes in the power supply.

It will be understood that each of the thyristors 83, 85 and 86 have a control contact which may be selectively switched hard on and hard off to permit current to flow through the thyristor.

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The second switching element 84 operates to precharge the capacitors in the capacitor bank 74 during a precharge operation. During the precharge operation which occurs immediately prior to the energising of a heating coil, thyristors 85 and (86) are switched on whilst thyristor 83 is maintained off. It will be understood that rather than using a dual thyristor arrangement a single larger thyristor could be used. The timing of the turning on and off of the thyristors is controlled so that approximately two seconds later the control gate of thyristor (83) is switched so that power is supplied to the induction heating coil. The precharging of the capacitor bank is to reduce the initial surge on the power supply 41 when a heating coil is initially to be energised. It will be understood that embodiments of the present invention may be utilised without switching element 84 and capacitor bank 74 when the restraint of power surges on a power supply are not of importance.

25 The inductor 90 may be one of the heating coils 31 to 34 indicated in figure 2 and may be connected to the power supply circuitry 40 via Tombac connectors 91 and 92 or other suitable connections.

30 By controlling the turning on and turning off of switching elements 81 and 84 power may be supplied to the heating coil 90 associated with the respective power supply circuit 40. The energising of the coil 90 induces a current to flow in the metal heating vessel adjacent to

the coil. This has a heating effect. When two adjacent heating coils such as coils 31 and 32 in figure 2 are energised simultaneously the control gate of thyristor 83 is supplied with a control signal to switch the thyristor on. In this way the current induced to flow in the melting vessel 15 by both coils 31 and 32 will, as well as having a heating effect, cause an interaction between electromagnetic fields such that the weaker field is enhanced by the adjacent stronger fields and thus balance power demand across the energised zones. This occurs if the same two phases are selected at (43) and the supply and return legs are the same orientation on each of the zones (i.e. the direction of the electromagnetic fields are the same) and as a result multiple heating coils may be energised at one time.

Temperature sensors (not shown) such as thermocouples may be located within and around the melting vessel to sense the temperatures at particular regions of the vessel. These readings may be used to control the energising of particular coils around the melting vessel so as to maintain the temperatures within predetermine threshold limits.

Embodiments of the present invention provide a way of heating zones of the main vessel body. The heating zones are subject to a mutual inductive effect which induces fields into the adjacent zones due to the mutual coupling of the induction media, the vessel, itself. This mutual coupling is removed from adjacent zones that are not firing concurrently by the isolation provided by the thyristor module 81. However when adjacent heating coils and thus adjacent zones are firing simultaneously the mutual coupling is permitted which balances the total

power delivered equally across the energised zones. 50  
Hertz induction heating coils 31 to 34 may be utilised in  
which the power is derived from mains frequency stepped  
down through a multi-tap auto-transformer to provide a  
5 coarse power level setting via contactors. This  
adjustment sets the amount of power delivered to the  
induction coil when the circuit is energised. Fine  
control of heat applied to respective zones is gained by  
control of turning thyristors in a switching element 81  
10 on or off in a time proportional manner derived from  
control circuits using feedback from the vessel  
thermocouples.

Embodiments of the present invention provide a heating  
15 system which can use 50 Hertz power supplies. Such power  
supplies are readily available and produce a wider  
magnetic field having more penetration. This enables  
melting vessels to have a thick wall which increases the  
lifetime of the metal vessel and reduces thermal stress.

20 Embodiments of the present invention have been described  
hereinabove by way of example only. It will be  
understood that modifications to the specifically  
described examples may be made without departing from the  
25 scope of the present invention.